Importance of Silicic Magmatism on the Moon

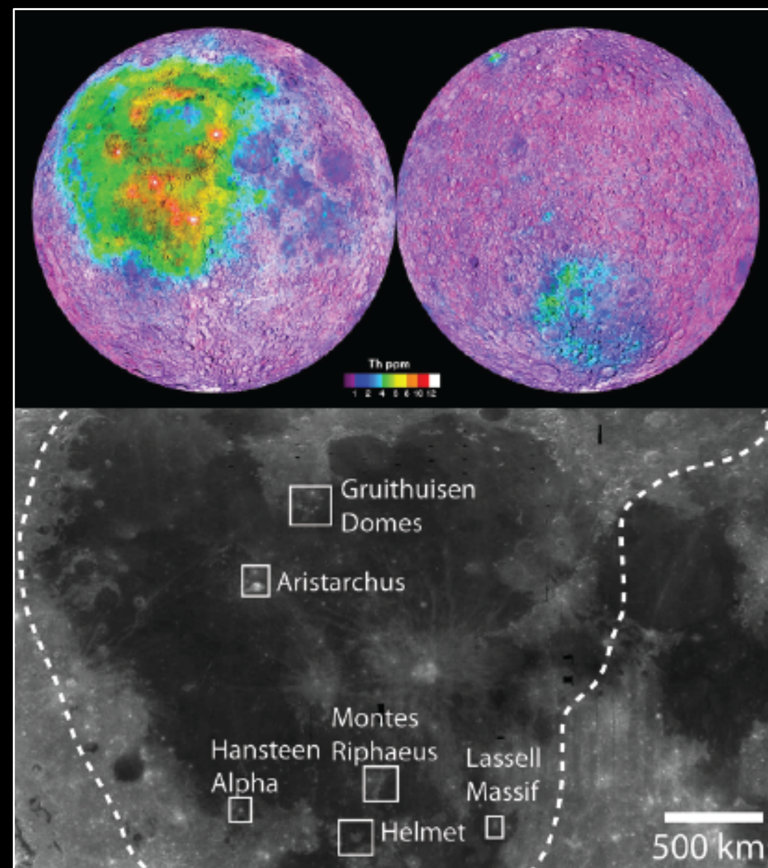
Justin I. Simon, Roy Christoffersen, Ryan D. Mills, D. Kent Ross, and Michael. Tappa
Center for Isotope Cosmochemistry and Geochronology,
NASA-Johnson Space Center

Conel M.O'D. Alexander, DTM

CICG
Center for Isotope Cosmochemistry and Geochronology
Exploration Integration and Science Directorate
NASA Johnson Space Center

Remote sensing suggests substantial regions of the Moon with high silica rocks:

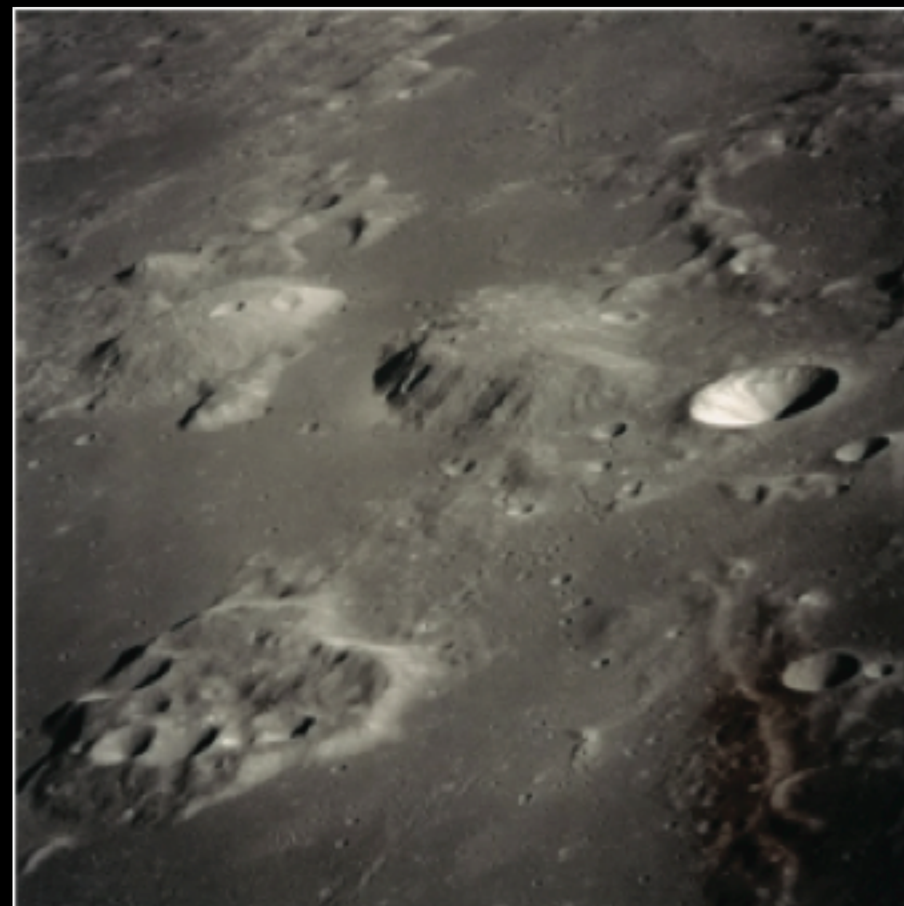
The Diviner Lunar Radiometer Experiment (Glotch et al., 2010; Greenhagen et al., 2010) expands upon evidence obtained by the Lunar Prospector for widespread silicic lithologies.



Clementine 750-nm mosaic showing the locations where Diviner remote sensing data indicate features with silicic compositions (e.g., Glotch et al. 2010).

Silicic Melts Typically Enriched in Water:

Generation and extraction of such silicic melts over time likely affects the distribution and budget of incompatible elements and molecular species (i.e., radiogenic heat producing elements and volatiles) in the lunar interior.



The silicic Gruithuisen Domes (36°N, 40°W). Image courtesy of the LPI.

Origin of silicic magmas on the Moon:

Three main hypotheses for generating high silica melts on the moon:

1) Fractional crystallization with silicate liquid immiscibility (SLI)

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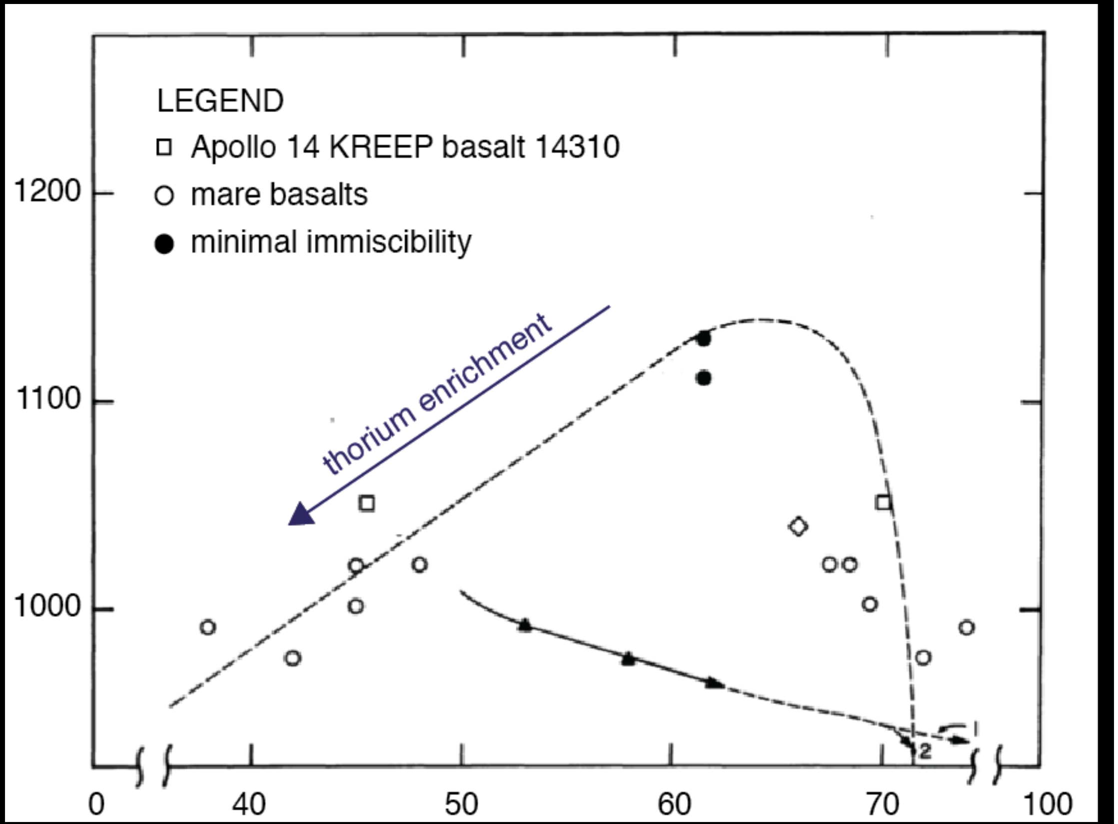
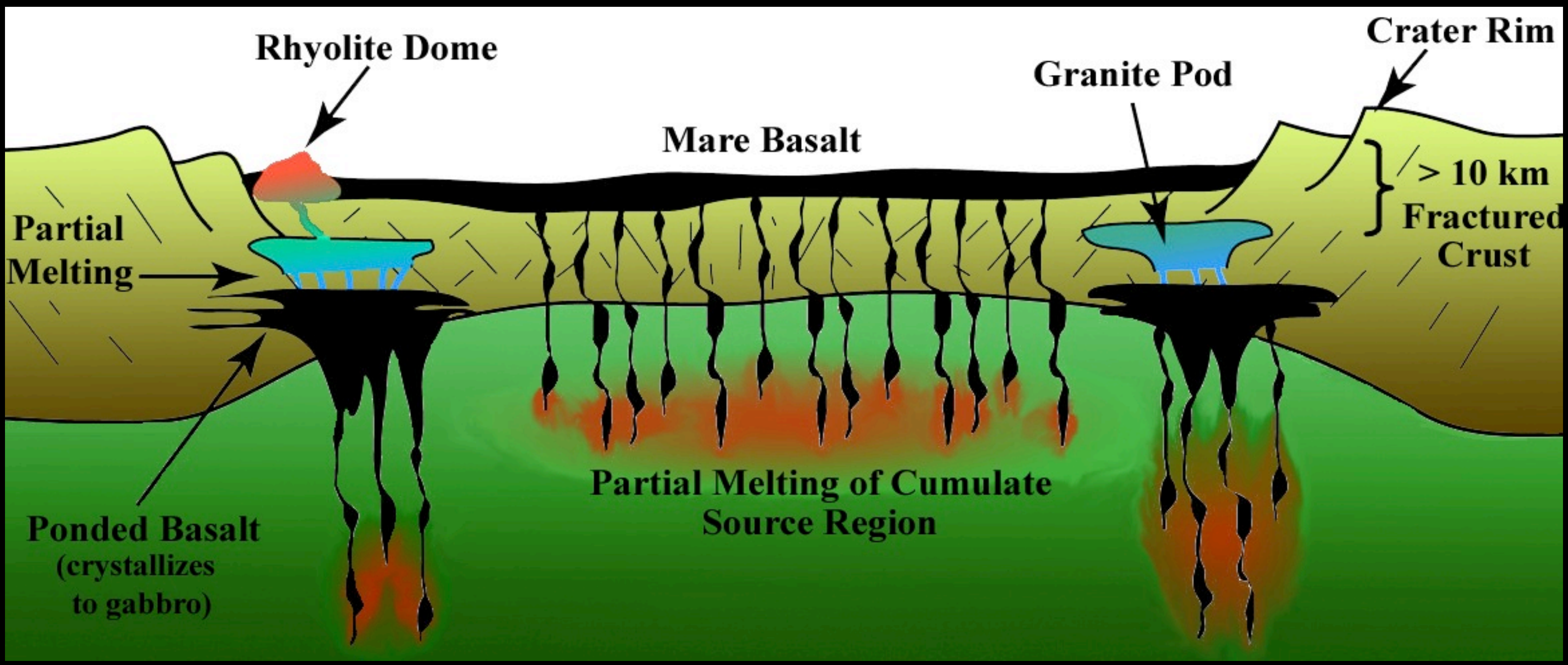


SiO_2

Granite/Fe-enriched basalt solvus from Rutherford et al. (1976). One problem with SLI is that Th should partition into the mafic melt, and the high silica rocks on the moon are enriched in Th.

Origin of silicic magmas on the Moon:

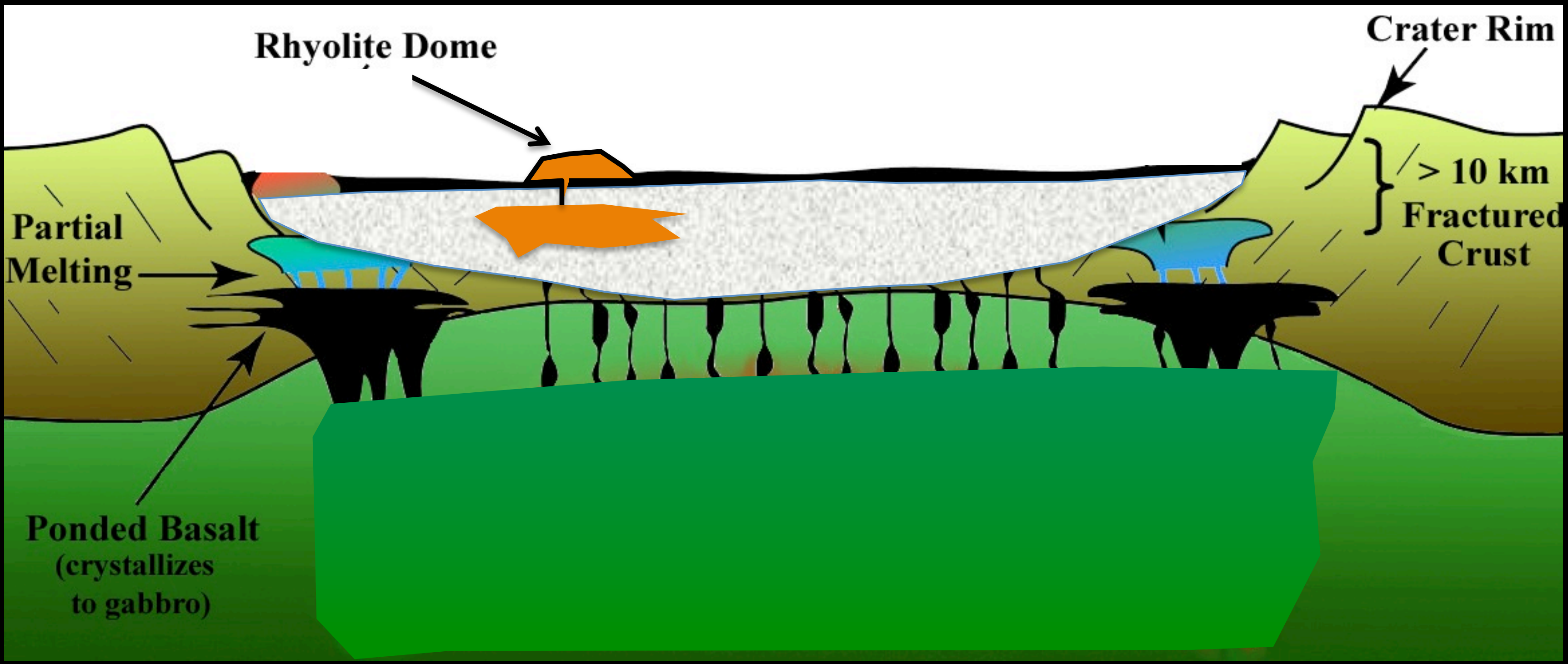
2) Partial melting of preexisting crust



Schematic diagram from Hagerty et al. (2006) showing basaltic magmas underplating preexisting crust and erupting onto the lunar surface.

Origin of silicic magmas on the Moon:

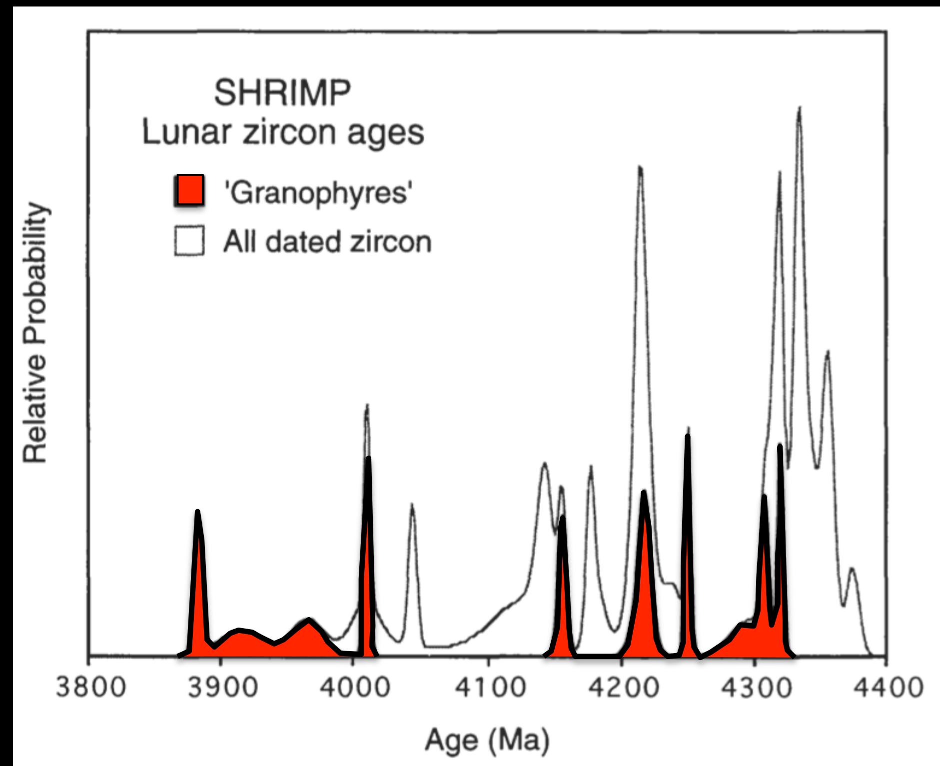
3) Differentiation of impact melt sheet



Exogenous heat source, i.e., impact remobilizes and ultimately concentrates water, halogens, and incompatible elements in the crust.

Isotopic data indicate silicic magmatism from ~4.3 to 3.9 Ga:

Unclear if silicic magma generation was protracted or punctuated, and if so by what?

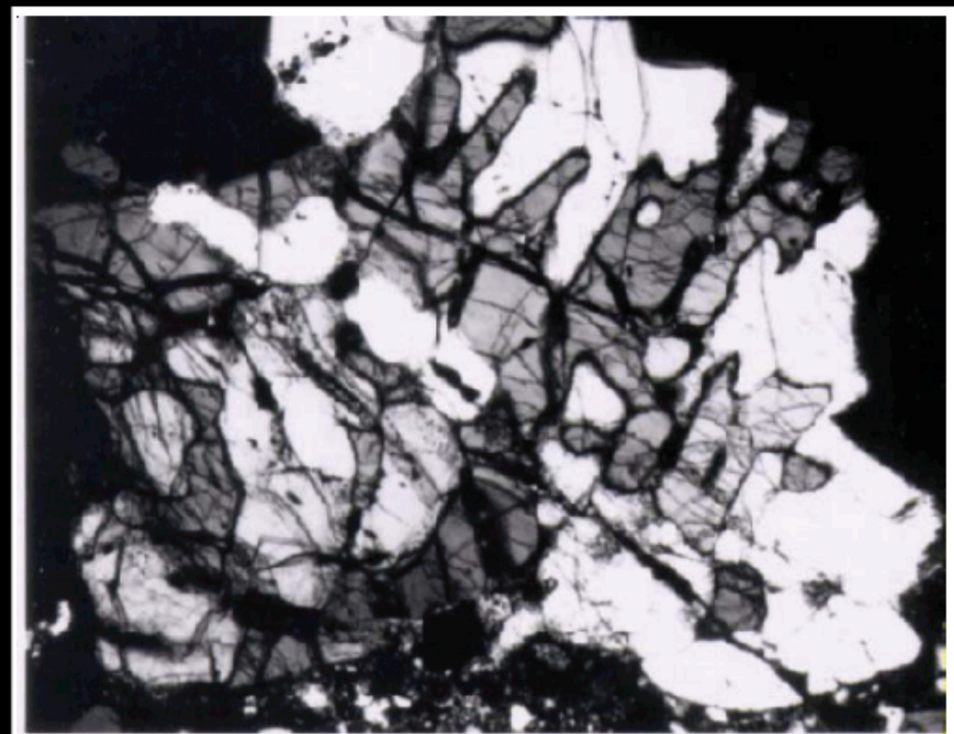


Summary of lunar zircon ages determined by ion probe. Figure is from Meyer et al. (1996). U-Pb zircon data from Taylor et al. (2009) show a similar temporal distribution.

Basic Approach:

We are analyzing granites and other evolved samples collected from PKT during the Apollo missions and meteorites that likely originated from compositionally similar terrains on the Moon (K- and Th-rich areas).

In thin section 14321, 1027 (Meyer et al., 1996)



The field of view is 1.8 x 2.3 mm.

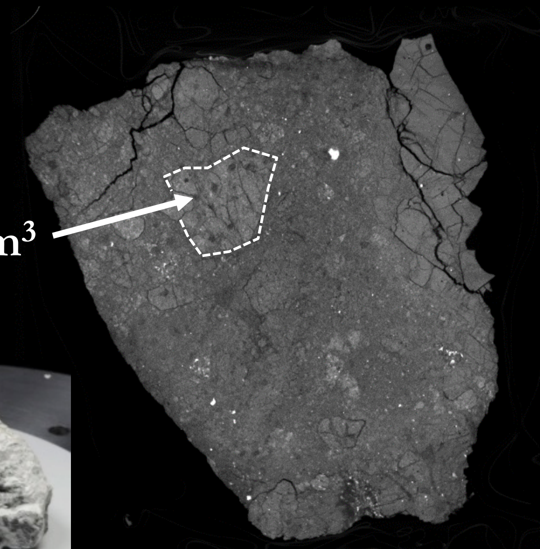
Photomicrograph showing the texture of silica and K-feldspar intergrowth in clast 14321, 1027. White is K-feldspar, gray is silica and black is epoxy. Its major and trace element chemistry are typical for granite.

Coordinated Analyses:

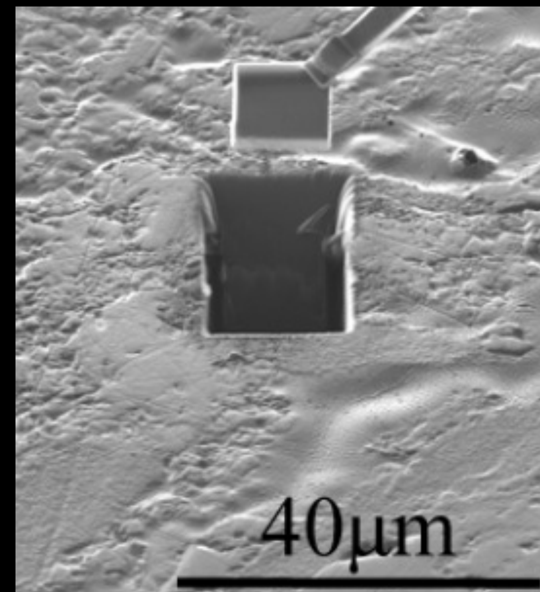
14321 lunar breccia

Clast = 0.637 cm^3
Clast = ~1.9 g

Micro CT scan slice

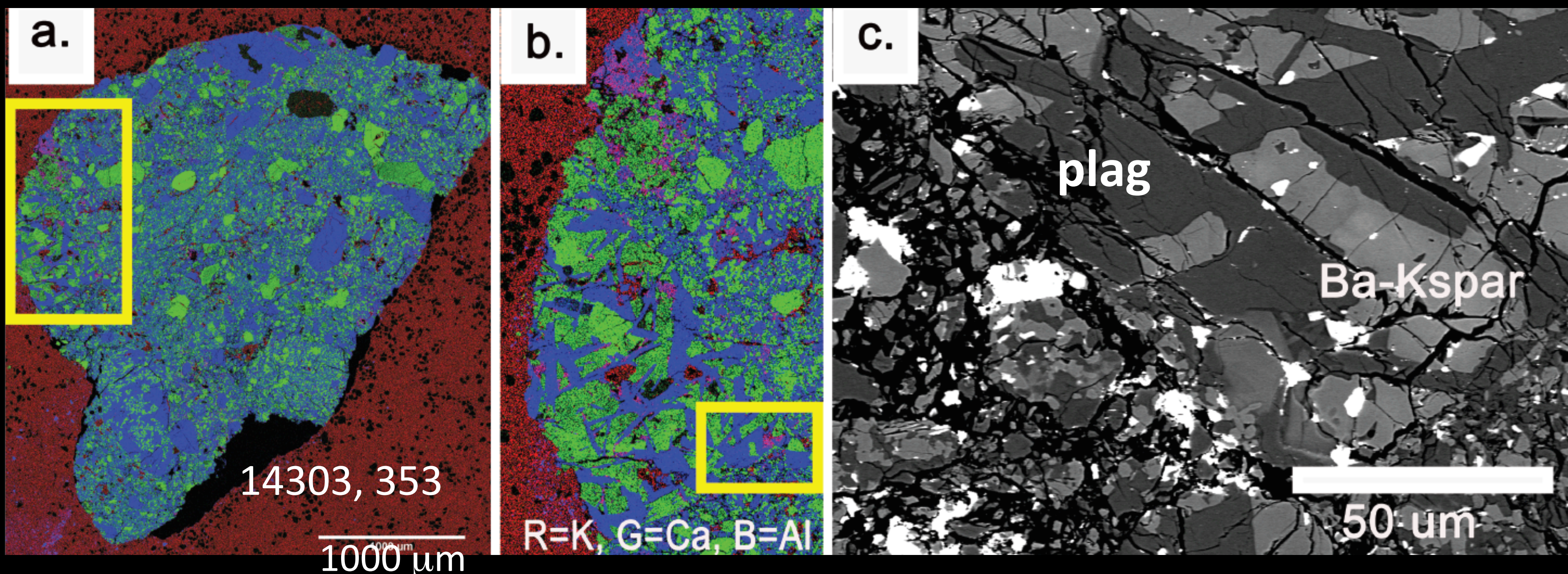


FIB section "lift out"



- Petrologic and geochemical studies (SEM, EPMA, and TEM)
- Volatile abundances (ion microprobe)
- K-Ca and Rb-Sr isotope systematics (TIMS)

Clasts are typically small, rare, and potentially disturbed by younger events:



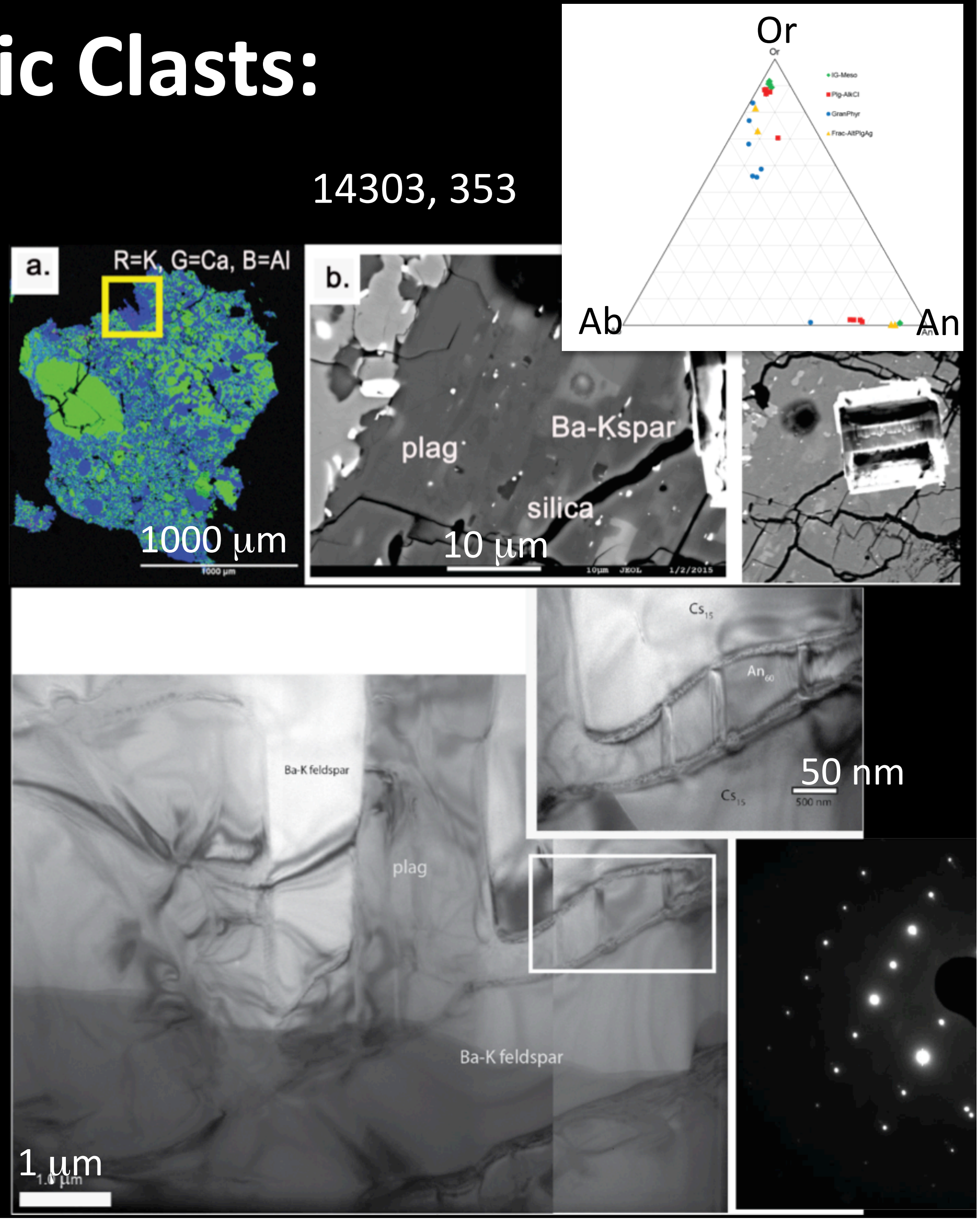
Assessment of age and volatile abundance begin after sequential analytical SEM, field-emission EPMA, and FIB-supported field emission STEM studies of the granitoid clasts.

Diversity of Silicic Clasts:

Locally abundant alkali feldspar.

Plagioclase diffraction patterns are consistent with rapid cooling as would occur in a very shallow, possibly even volcanic, igneous setting.

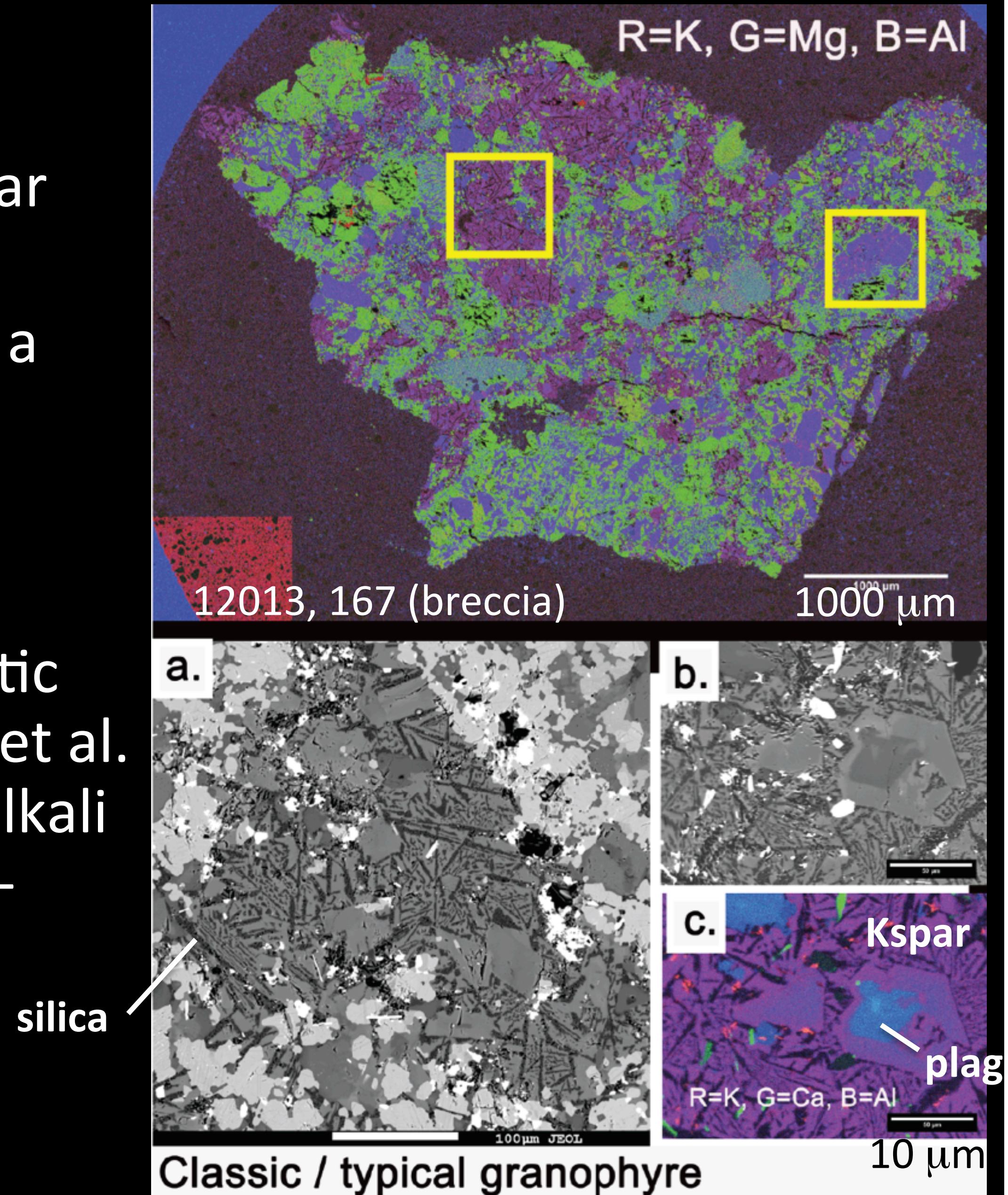
14303, 353



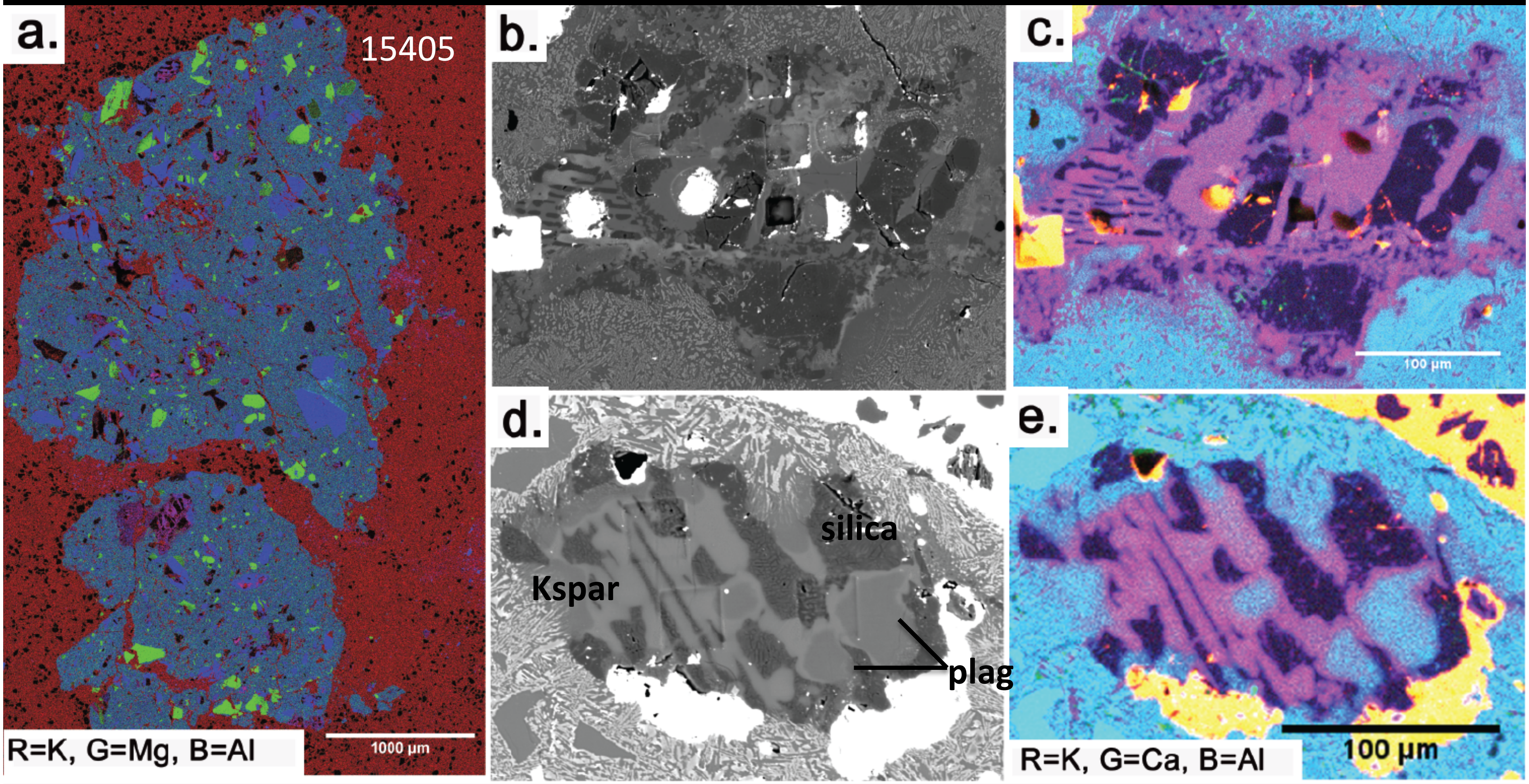
Diversity of Silicic Clasts:

The texture and Ba-K feldspar compositional variability suggests this is a product of a rapidly crystallized melt.

Textures analogous to granitic particle reported by Seddio et al. (2013); high abundance of alkali feldspar imply pockets of re-crystallized granitoid.



Diversity of Silicic Clasts:



The microstructure likely also represent rapid crystallization, similar to 'classic' granophyre, but with slightly different controls on the microstructural development, including slower cooling.

A couple success stories to highlight:

- Granite clast 14321, 1067 (Simon et al., 2011; Mills and Simon, 2012)
- Granitoid clast 15405, 78 (Mills et al. 2013; in review)

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Astromaterials Exploration Research Directorate
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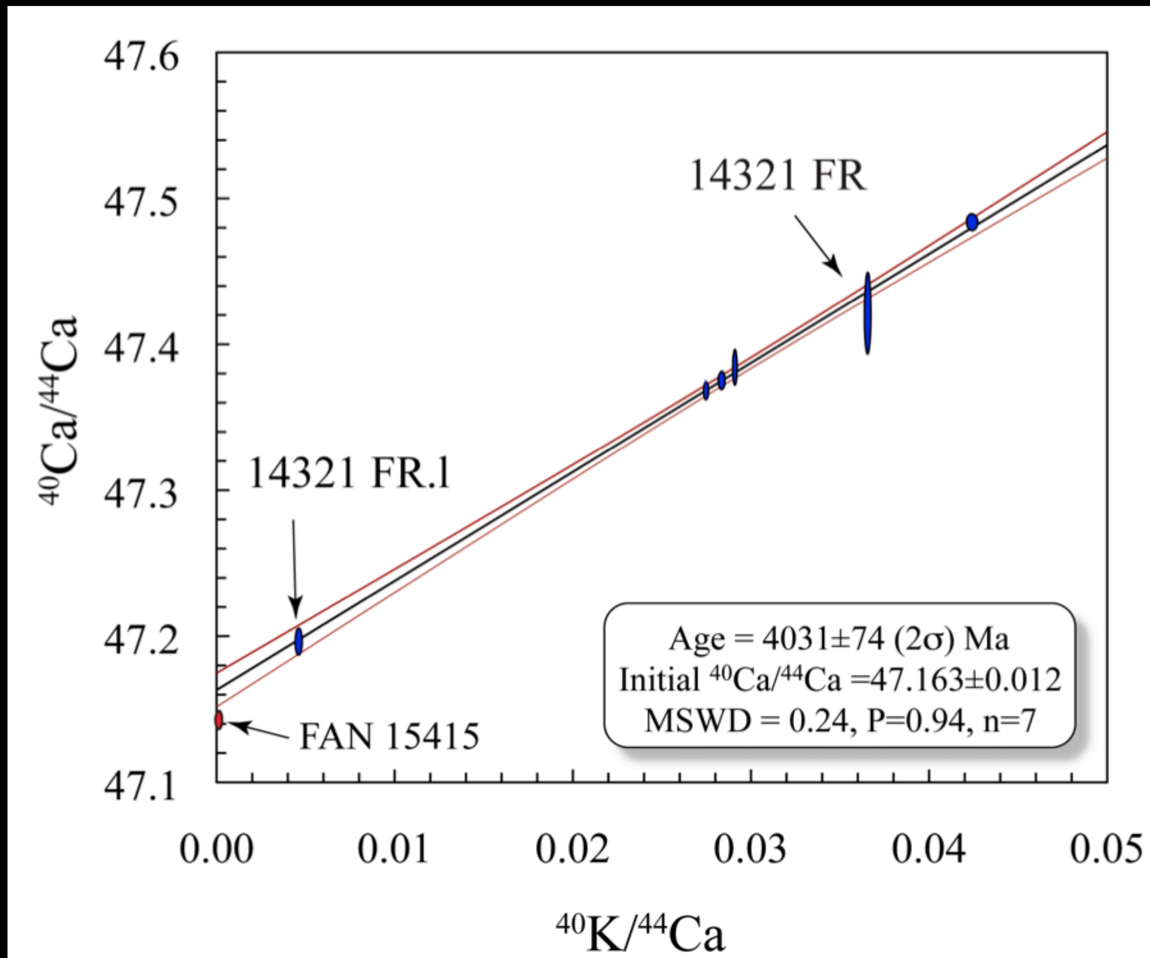
K-Ca and Rb-Sr isochrons using residual materials from granitic clast in 14321 (Warren et al., 1983):

- 2.9 mg bulk rock (14321 FR)
- 4.15 mg of acid washed residues (14321 FR.r)
- 0.7 mg leachate derived from the washing (14321 FR.l)
- Ferroan anorthosite (FAN) 15415 for the initial Ca and Sr compositions of pristine highland rocks.

K-Ca & Rb-Sr Analyses at NASA JSC:

- The lunar samples are spiked with ^{40}K-^{48}Ca and ^{87}Rb-^{84}Sr mixed spikes
- Samples dissolved and/or leached by acids
- Coordinated K & Rb, Ca, and Sr chemical purification
- TIMS analysis (via Triton)

K-Ca isochron (refining Shih et al. 1993)



Leaching procedures are conduced to produce greater spread and leverage of isochrons. Solar system initial: $^{40}Ca/^{44}Ca$=47.148 (Simon and DePaolo, 2009); FAN $^{40}Ca/^{44}Ca$=47.152±0.006

Age concordance for 14321, 1067:

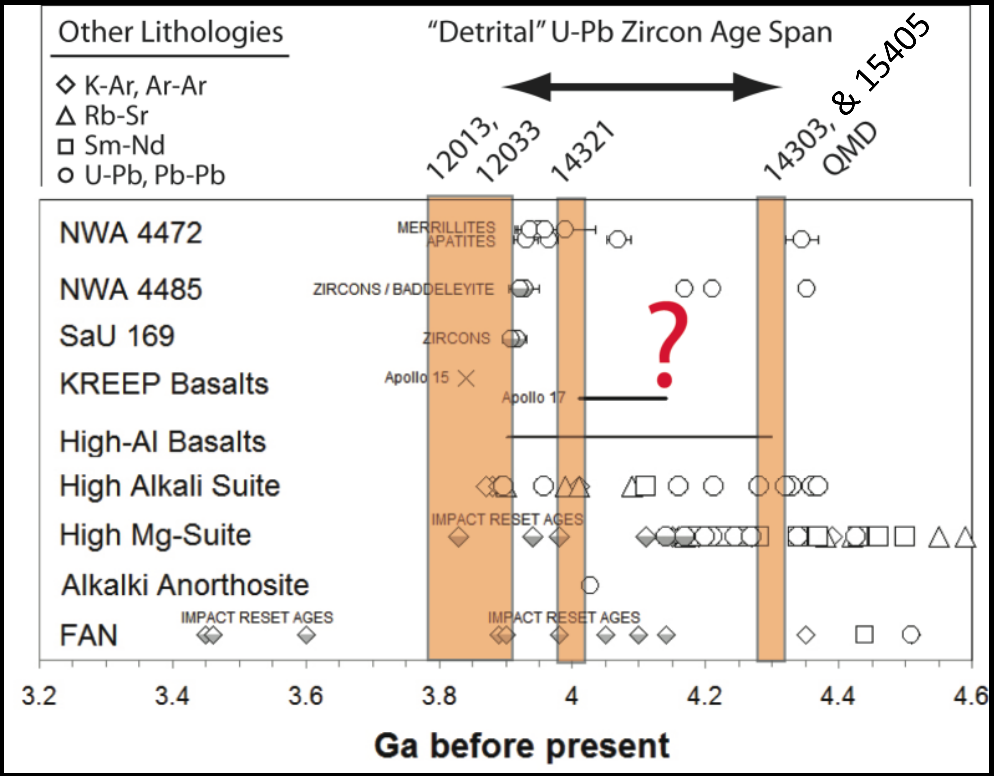
Refined:

K-Ca age:

4031±74 Ma (2σ)

Rb-Sr age:

4052±81 Ma (2σ)

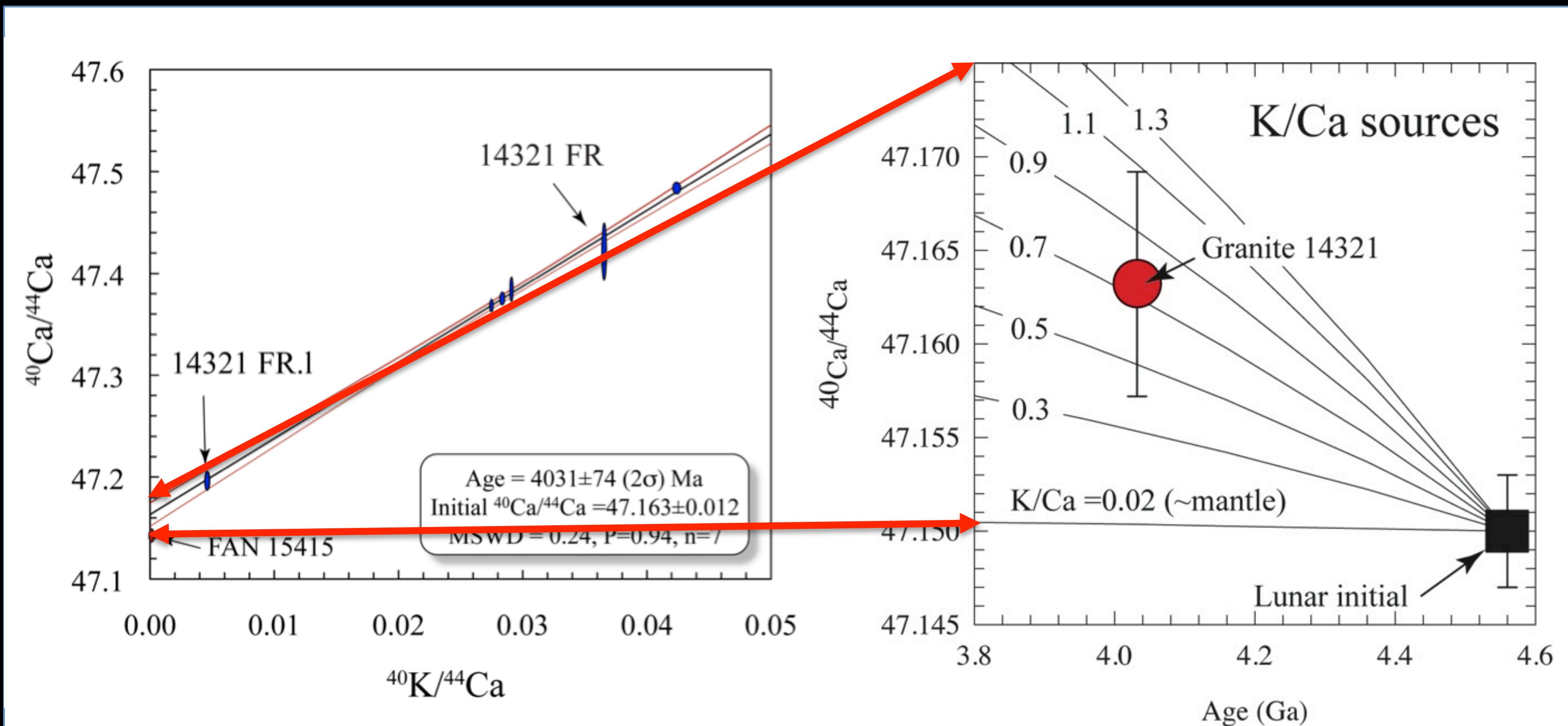


Match reported:

U-Pb zircon age of 3965±50 Ma (Meyer et al., 1996)

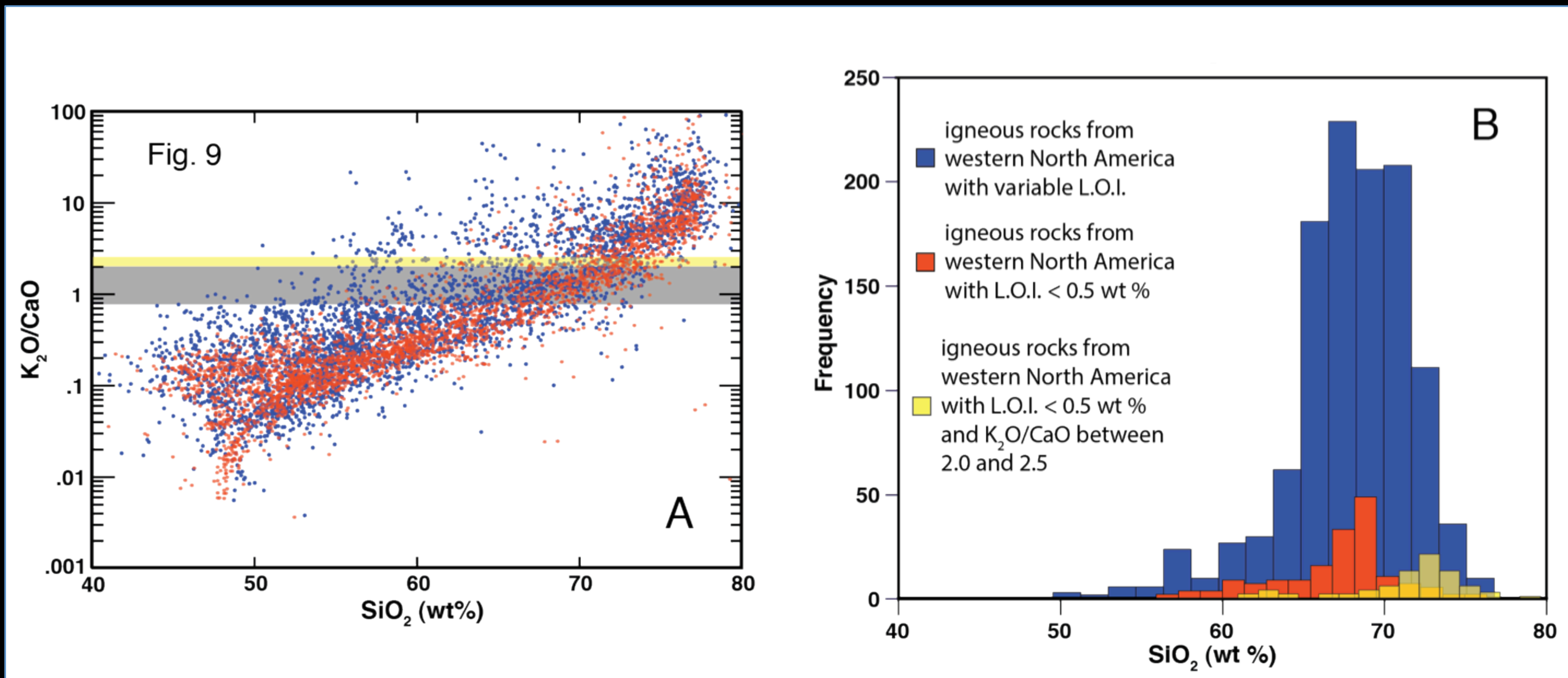
Sm-Nd age of 4100±200 Ma (2σ) (Shih et al., 1985)

Source (K/Ca): all about the intercept



Calculated K/Ca ratio of the parental material for granite clast from Apollo sample 14321.

Predicting the Sources of the Silicic Clasts:

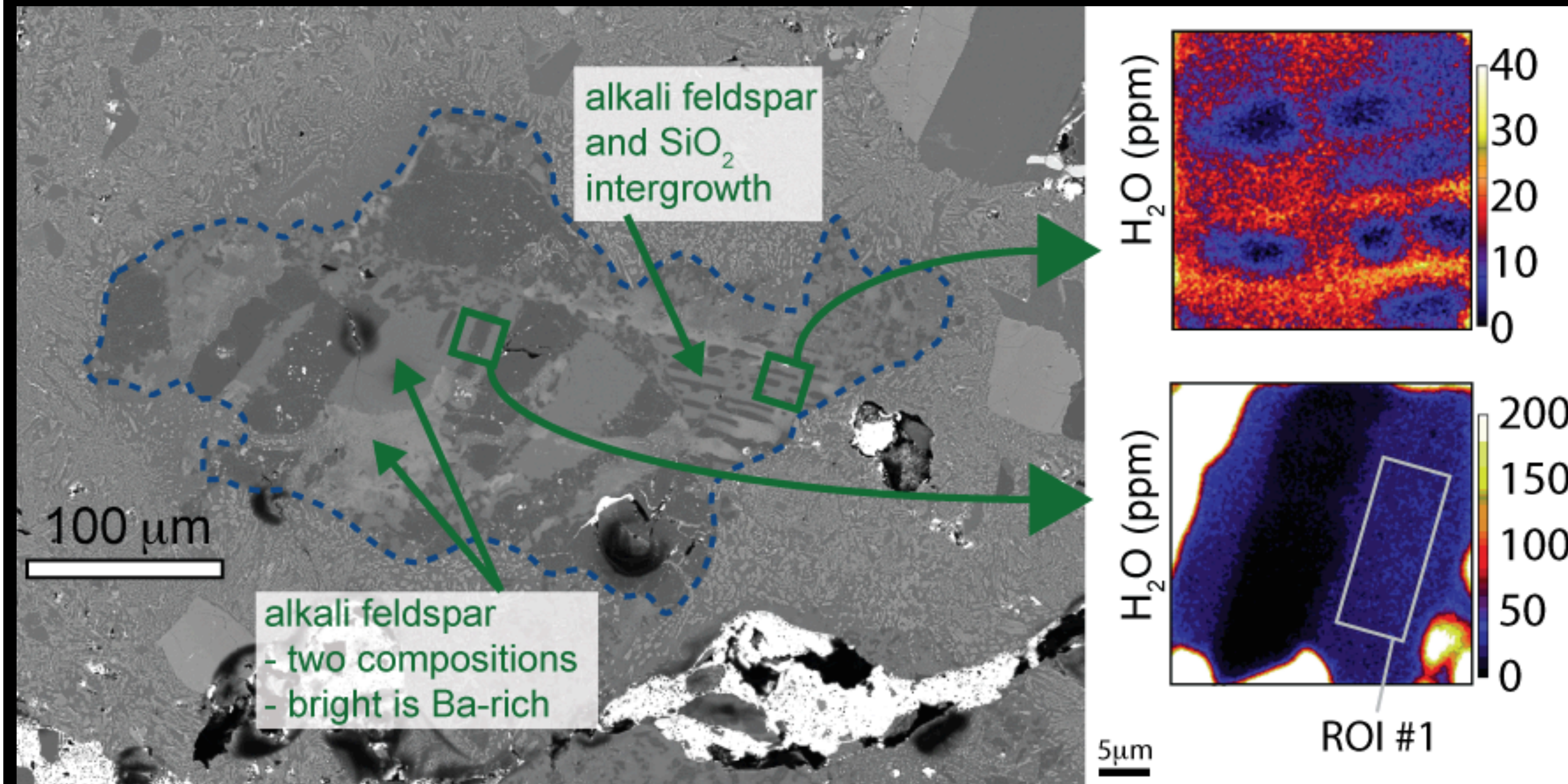


(A) Igneous rocks from the western US with L.O.I. < 0.5 % (all data extracted from www.navdat.org). Gray bar is the calculated K_2O/CaO ratio of the parental material for granite clast from Apollo sample 14321.

(B) Histogram of SiO_2 for data that fall within the gray bar in A.

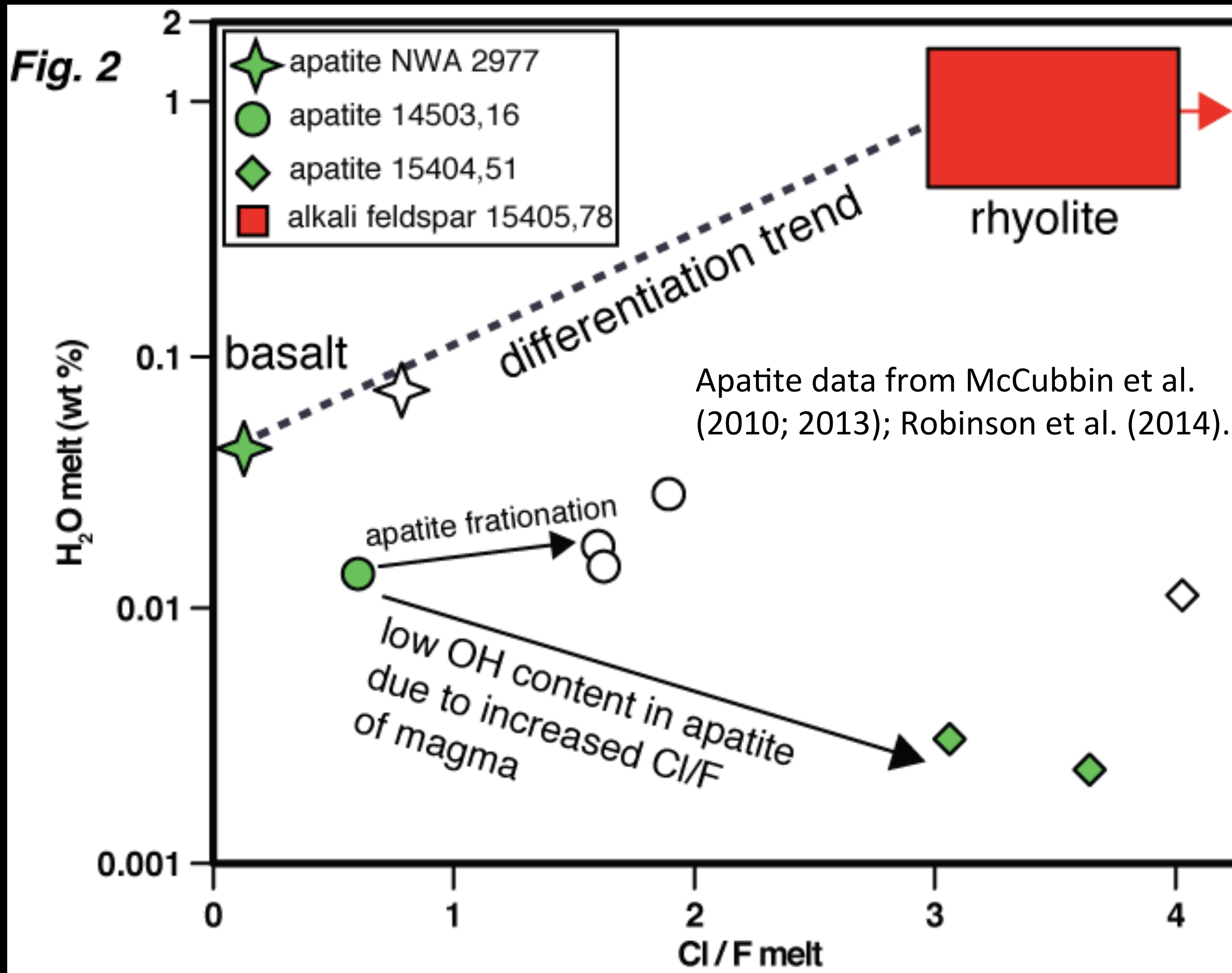
NanoSIMS Volatile Analysis at DTM:

15405, 78 (shallowly emplaced igneous texture)



Ion images obtained by NanoSIMS in KREEP-rich clast. Water correlates with mineralogy. The alkali feldspar consistently has ~20 ppm H_2O. The silica phase has similar water contents as the blank obtained on anhydrous glass (~ 2 ppm).

Estimated water content versus Cl/F ratio for lunar magmas:



Mills et al. (in review)

Summary of Work in Progress:

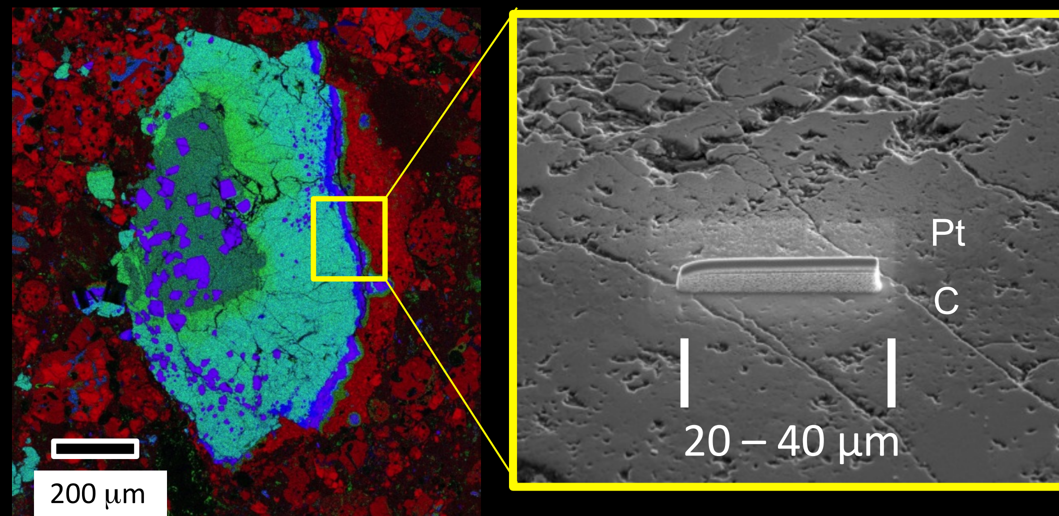
- 14321, 1067 provides a robust ~ 4.0 Ga igneous crystallization age and already evolved source.
  (Simon et al., 2011; Mills and Simon, 2012)

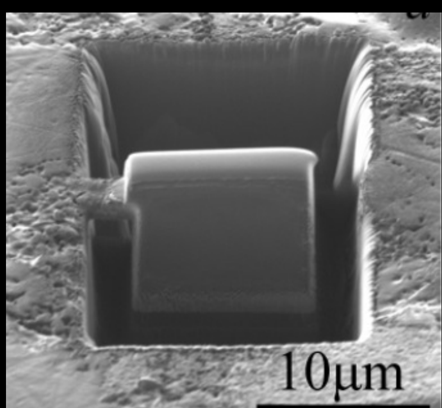
- 15405, 78 provides intrinsic water abundances and implies ~ 0.5 to 1.3 wt. % water in granitic melt 4.3 Ga ago.
  (Mills et al. 2013; in review)

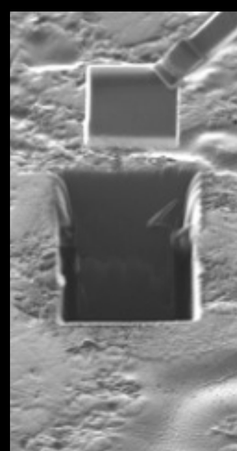
If granitic melts are generally this 'wet' and represent a distilled component of the urKREEP reservoir then the bulk Moon water content would have been depleted by ~ 10 ppm by ~4 Ga, which would reflect a significant effect on the water content of the already dry bulk Moon.

We have been allocated a number of silicic clasts, expect to find more using microCT scanning and thus have a lot of exciting sample characterization and isotopic/volatile analyses to do!
(e.g., Mills et al., 2014; Christoffersen et al., 2015)

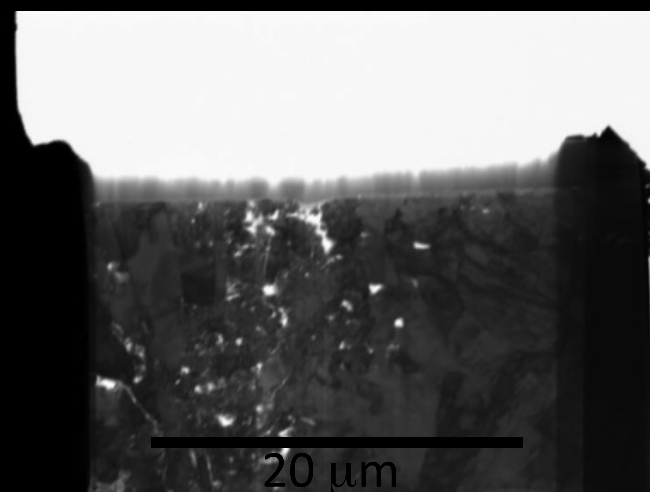
[redacted]


200 μm
Pt
C
20 – 40 μm


10μm




20μm


20 μm

Analytical Field-Emission TEM and Focused Ion Beam (FIB) Sectioning– Minimally Invasive Surgery on Meteorites:

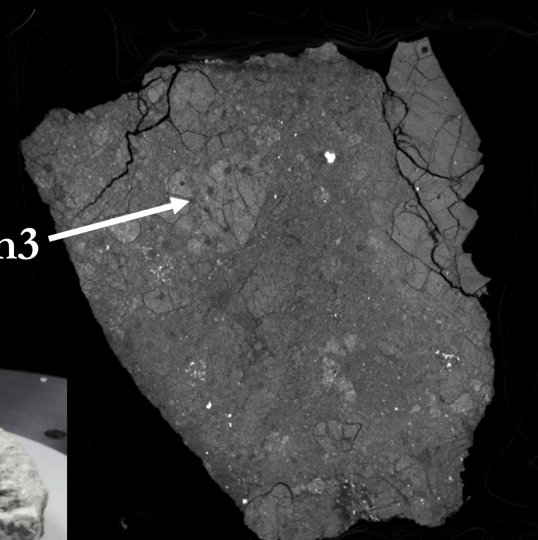
CT scan human knee

Arthroscopic Surgery

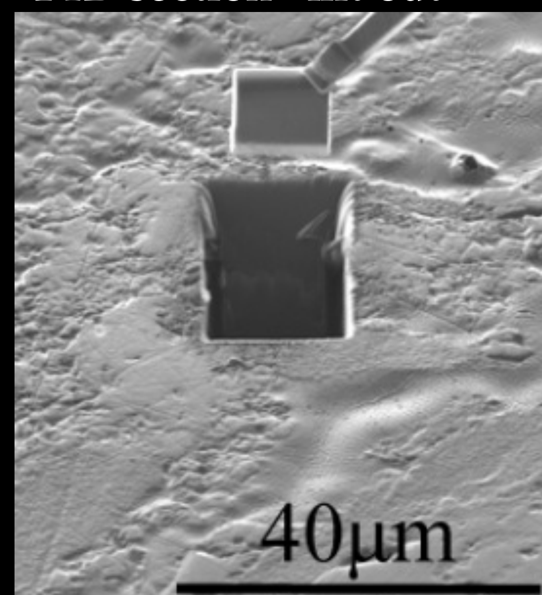
Micro CT scan slice

14321 lunar breccia

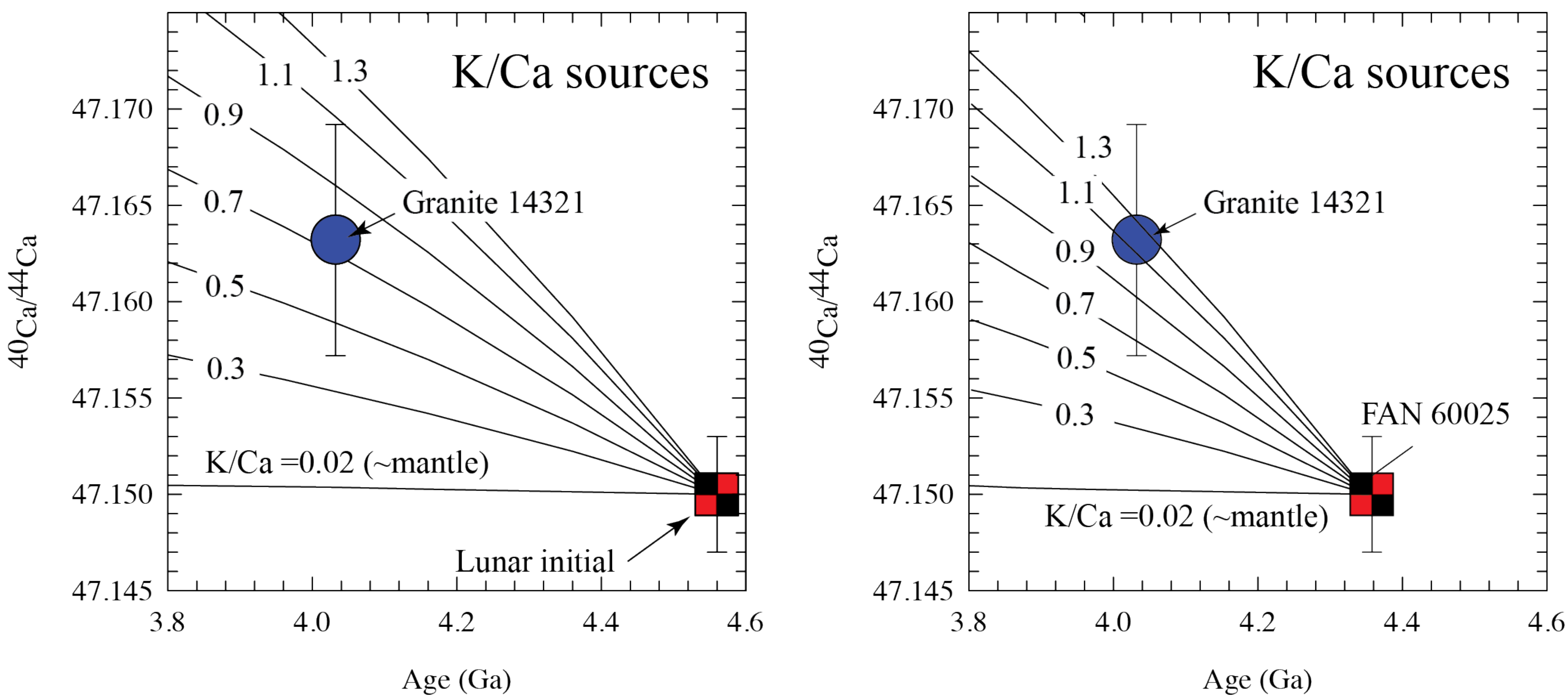
Clast = 0.637 cm3
Clast = ~1.9 g



FIB section "lift out"

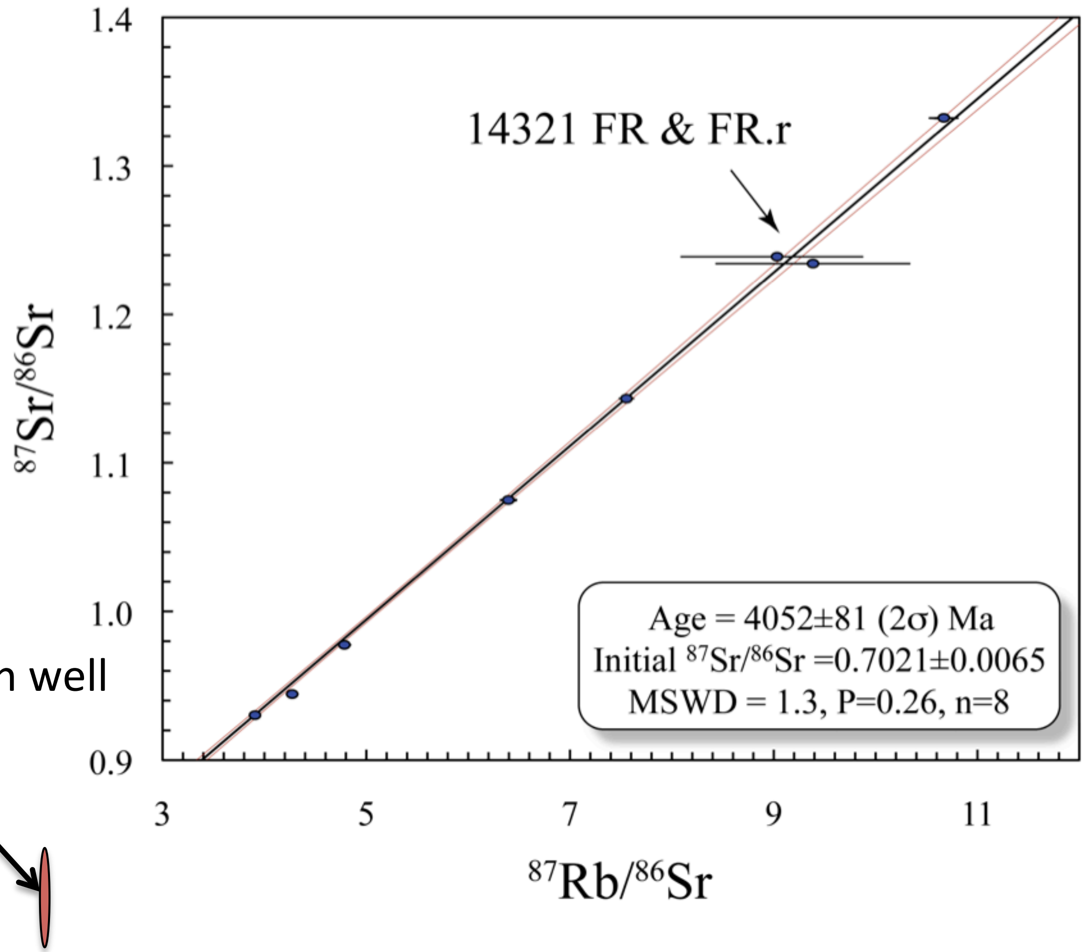


Source (K/Ca): younger age of FAN?



If new 4.360 Ga age for FAN 66025 is used (Borg et al., 2011), this requires that the source of granite 14321 may have been more enriched (K/Ca ratio ~1.5) and/or not the same as FAN.

"Improved" Rb-Sr isochron



Leachate didn't run well

FAN 15415 WR $^{87}Sr/^{86}Sr$ = 0.699251±0.000010